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Three-Dimensional Imaging in Paleoanthropology and Prehistoric Archaeology

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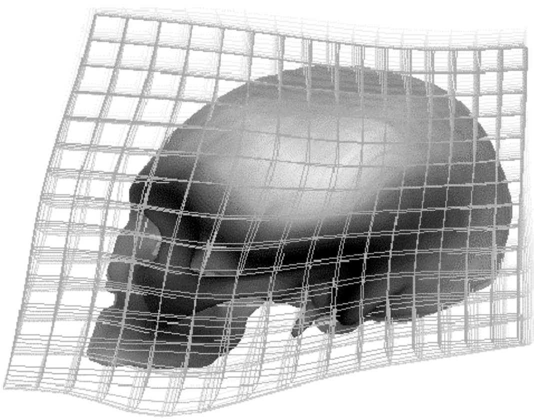

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HOMINID TOOTH PATTERN DATABASE (HOTPAD) DERIVED FROM OPTICAL 3D TOPOMETRY

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Résumé: HOTPAD est une plate-forme d'acquisition des données tridimensionnelles dentaires. Un système de topométrie optique portable a été utilisé pour réaliser l'acquisition en haute résolution des surfaces de dents des premiers espèces du genre Homo. Dans cette étude, nous présentons le concept et la structure du système HOTPAD à partir de l'analyse d'une deuxième molaire d'un hominidés de Java, Indonésie, conservée au Forschungsinstitut Senckenberg de Francfort. Des modèles de couronne dentaire reproduites en réalité virtuelle ont été utilisés pour les calculs morphométriques. Nous présentons des méthodes permettant l'extraction et la visualisation des distances, surfaces et volumes quelque soit la forme des couronnes dentaires. De plus, d'autres paramètres comme la forme des relief, la surface des cuspides, les arrondis et les angles sont analysés pour montrer l'étendue des possibilités de ces scanners surfaciques à haute résolution pour l'étude de la morphologie des molaires et de l'usure dentaire.

Abstract: HOTPAD is a platform for providing three-dimensional data of teeth. A portable optical topometry system is used here to acquire high-resolution point clouds of tooth surfaces of early Homo species. In this contribution we introduce the concept and structure of HOTPAD, on the basis of the early hominid second molar assemblage from Java, Indonesia, housed in the Forschungsinstitut Senckenberg in Frankfurt. Enhanced Virtual Reality models of molar crowns are used for morphometric calculations. Here we present methods to extract and visualize distance, area and volume parameters of overall shape of tooth crowns. Furthermore functional parameters such as relief shape, cusp area, sloping and angle are documented to explore possibilities of high-resolution surface scans for studying molar morphology and wear pattern.

CONCEPT OF HOTPAD

The idea of HOTPAD arose during a pilot study on digital documentation of tooth morphology. We tested an optical 3D topometrical system to acquire data of tooth crowns for the purpose of occlusal surface analysis. During this test it became clear that high-resolution virtual models would provide an efficacious means of obtaining precise metric data of teeth at a significant savings of time and effort.

HOTPAD is a quantitative image database of teeth based on high-resolution Virtual Reality (VR) models. It is an html-programmable platform to enable data acquisition from specimens for comparison and presentation. It can be used as a simple catalogue or an information centre, but it is also intended to be a forum for the discussion of new ideas and methods concerning tooth pattern analyses. Interested individuals are invited to view and survey low-resolution vrml-models, using a viewer such as Cosmoplayer or Cortona. Polygon files in higher resolution are also available for downloading. Colleagues can evaluate specimens in the collection for their own research purposes.

The first version of HOTPAD (Figure 1) contains information about teeth of early *Homo* species recovered by G.H.R. von Koenigswald from the island of Java, Indonesia. Material from the Sangiran collection housed in the Forschungsinstitut Senckenberg in Frankfurt am Main consists of three fragmentary skulls (Sangiran 2,3 and 4), one maxilla, six mandible fragments (Sangiran 1, 4, 5, 6a, 6b and 6c) and 52 single teeth (Sangiran 7.x) (von Koenigswald, 1940, 1950, 1954; Grine & Franzen, 1994). Because the stratigraphic context of most of these finds is not known with sufficient reliability, evolutionary researchers often neglect these specimens. Despite this caveat, in 2001 we began a long-term project on the reconstruction and quantification of early *Homo* tooth morphology with both the intentions of bringing this neglected sample to light and to develop and put into practice our 3D topometric method. The main goal is to recognize and interpret evolutionary trends in tooth shape development and change, such as megadonty in earliest *Homo*.

We describe here the technique of optical 3D topometry and methods of data extraction from virtual models. Measurements and basic comparisons of structural parameters are also available. New structural parameters are introduced to quantify and understand the occlusal surface of teeth and specific changes arising through wear.

OPTICAL 3D TOPOMETRY

For 3D-data acquisition we used the topometrical 3D-measurement system OptoTop (Breuckmann GmbH, www.breuckmann.com; Figure 2). The OptoTop 3D-sensor works on the principal of optical triangulation, based on a simple mathematical equation. Knowing the sensor geometry of the camera CCD makes it possible to calculate for each point at x and y, the height (z). The measuring method is refined through the combination of Gray-Code and Phaseshift techniques (Breuckmann, 1993). In the Gray-Code technique a special projector produces a sequence of fringe patterns of various grating periods on the object (Figure 3) and a CCD-

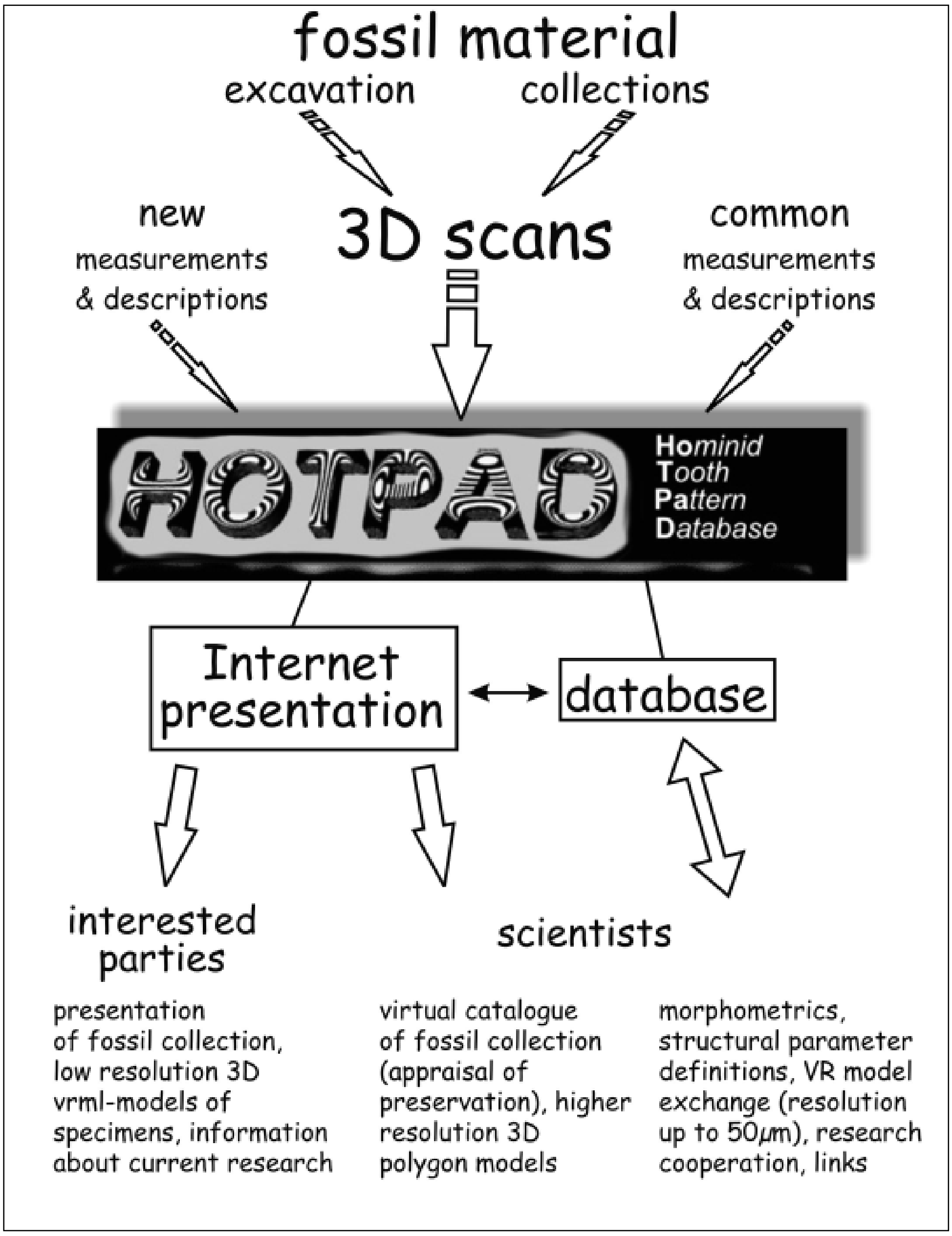


Figure 1 - HOTPAD is a virtual catalogue of fossil hominid teeth, including morphometric data of surface analyses. It contains virtual 3D surface models of specimens from the famous site of Sangiran on the island of Java, Indonesia. Interested parties and scientists all over the world can use HOTPAD as an information centre and source of data accessible via Internet.

camera (1x1.3k chip size), located at a certain angle towards the direction of illumination, records the object (e.g. tooth), simultaneously with each of the various projected fringes. After the Gray-Code pattern images have been acquired, the projector produces very fine sinuous stripe pattern onto the object, which is shifted about 90° after each image capture. A sophisticated computer calculation permits the extraction of x,y,z coordinate of each image point, through superimposition and analysis of each image. The 3D coordinates can be calculated pixel by pixel by means of these object patterns according to rules of triangulation.

In order to have a complete virtual model of a tooth we record the 3D-coordinates from several views. The number of views depends on the relief height, surface reflection, and complexity of the object. Experience shows that fossil tooth recordings require more image perspectives than modern teeth in order to have a reasonably complete model. Large differences in contrast and reflection render fossil surfaces more difficult to image, thus requiring individualized scan-parameter settings (e.g. repetition of the image sequence with several light intensity and contrast threshold settings). Powdering techniques using, for instance, ammonium chloride powder to evenly whiten the surface, can be very useful when variation in image contrast is high. Our experience with single teeth has indicated that between six and ten views are required before having a suitable model. Once all views are acquired they are aligned with PolyWorks, a modular software package from Innovmetric (www.innovmetric.com).

To obtain high-resolution point clouds we scan specimens with a measuring volume of 60x80x50 mm, producing for

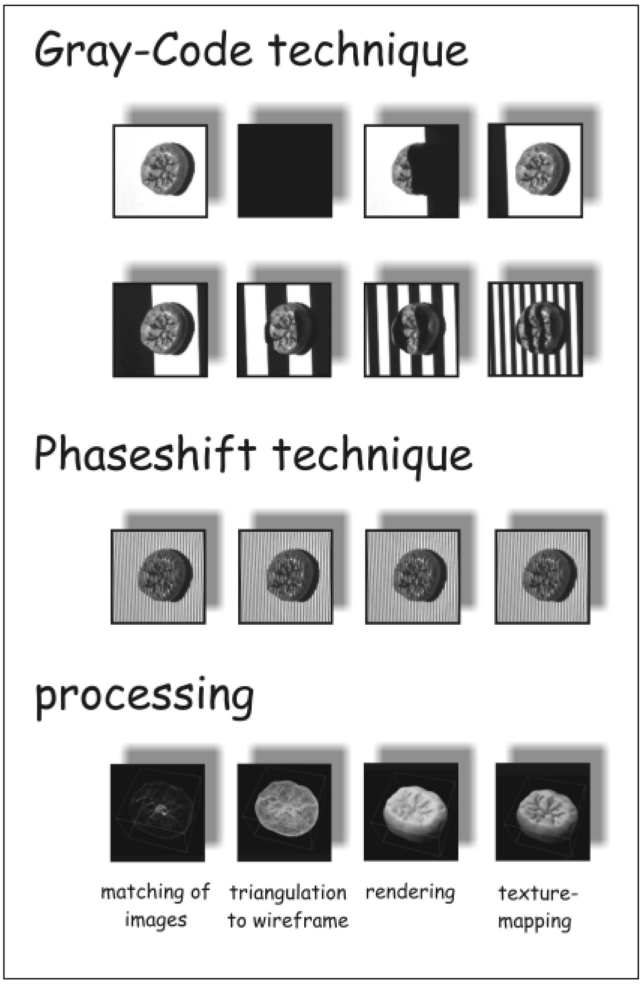


Figure 2 - The portable 3D system OptoTop consists of a CCD Camera and a fringe pattern projector. Calculation of 3D coordinates for each object point, recorded on the CCD chip, is based on the principle of triangulation. The distance d can be calculated, if the exact space between the CCD camera and projector (a), and the angle (a), are known.

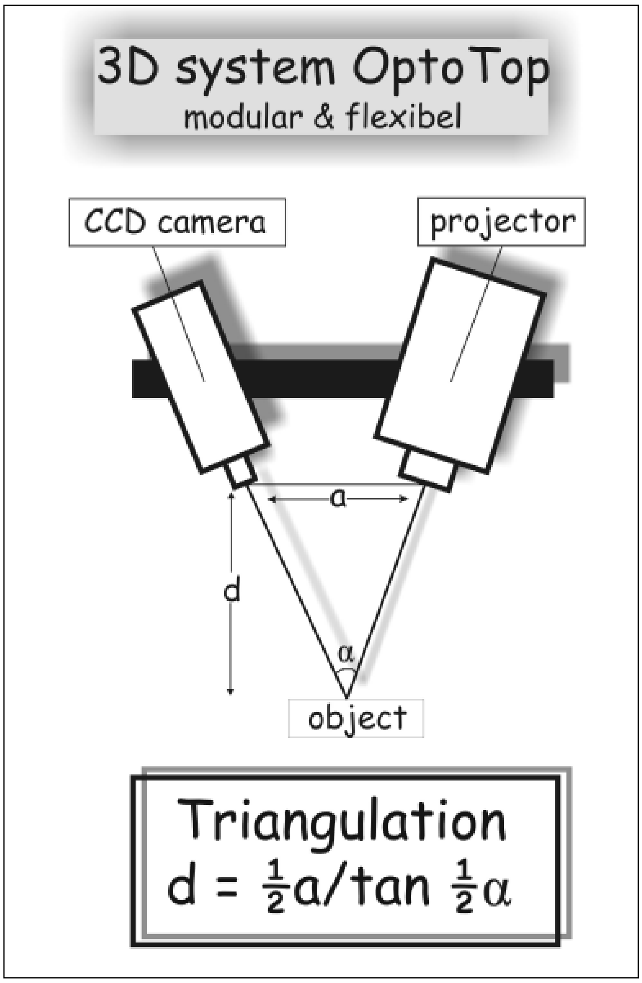


Figure 3 - The projector sends strip pattern with increasing number of lines on the object, while the camera is recording each image (Gray-Code technique). A high resolution point cloud results after the combination of Gray-Code and Phaseshift technique (projection of a sine shaped pattern and four times shifted about 90°) and a rather sophisticated computer calculation of the image stack. Further processing of the scans includes matching of images, triangulation to a wire frame model, rendering and original texture mapping.

each scan a maximum of 1.3 Million points. The resulting point clouds are matched from all views with a basic point grid of 50µm and an accuracy of +/- 25µm. We then import the point clouds into the editing, analysis, and visualisation modules of PolyWorks. The integrated triangulation tool calculates surfaces based upon three neighbouring points of the cloud (polygon meshing) (Figure 3). The surface of a tooth is thus rendered and can be studied with various measurement and analysis tools. Furthermore, because the topometric system is recording grey values for each point, the VR model is rendered with realistic surface contrasts (Figure 4).

Limits of three-dimensional surface rendering occur when the object shows extreme cavities or curvature and no angle position of the sensor can be found to illuminate object boundaries. Nevertheless pilot studies with different objects, like mammal teeth, skulls, long bones, fossil brain casts, as well as fossil and modern footprints (Kullmer et al., in press) have demonstrated that optical 3D-topometry is of multipurpose use in palaeontology and archaeology.

TOPOGRAPHIC RELIEF ANALYSIS OF TEETH

For more than 100 years palaeontologists have analysed teeth, particularly because many extinct species are only known from their dentitions. Teeth are a source of information about species affinity, dietary preferences and function, the environment, and evolutionary trends in tooth pattern development.

The chewing process works with extreme precision. Any deviation of occlusion from normal results in reduced effectiveness. Mastication is influenced by many factors such as jaw movement and the primary topography, or relief, of the teeth (primary relief). The spatial position of a tooth is also a limiting factor, determining how deep a specific cusp may dip into the corresponding basin of the occluding tooth. During the mastication cycle contacts occur between food

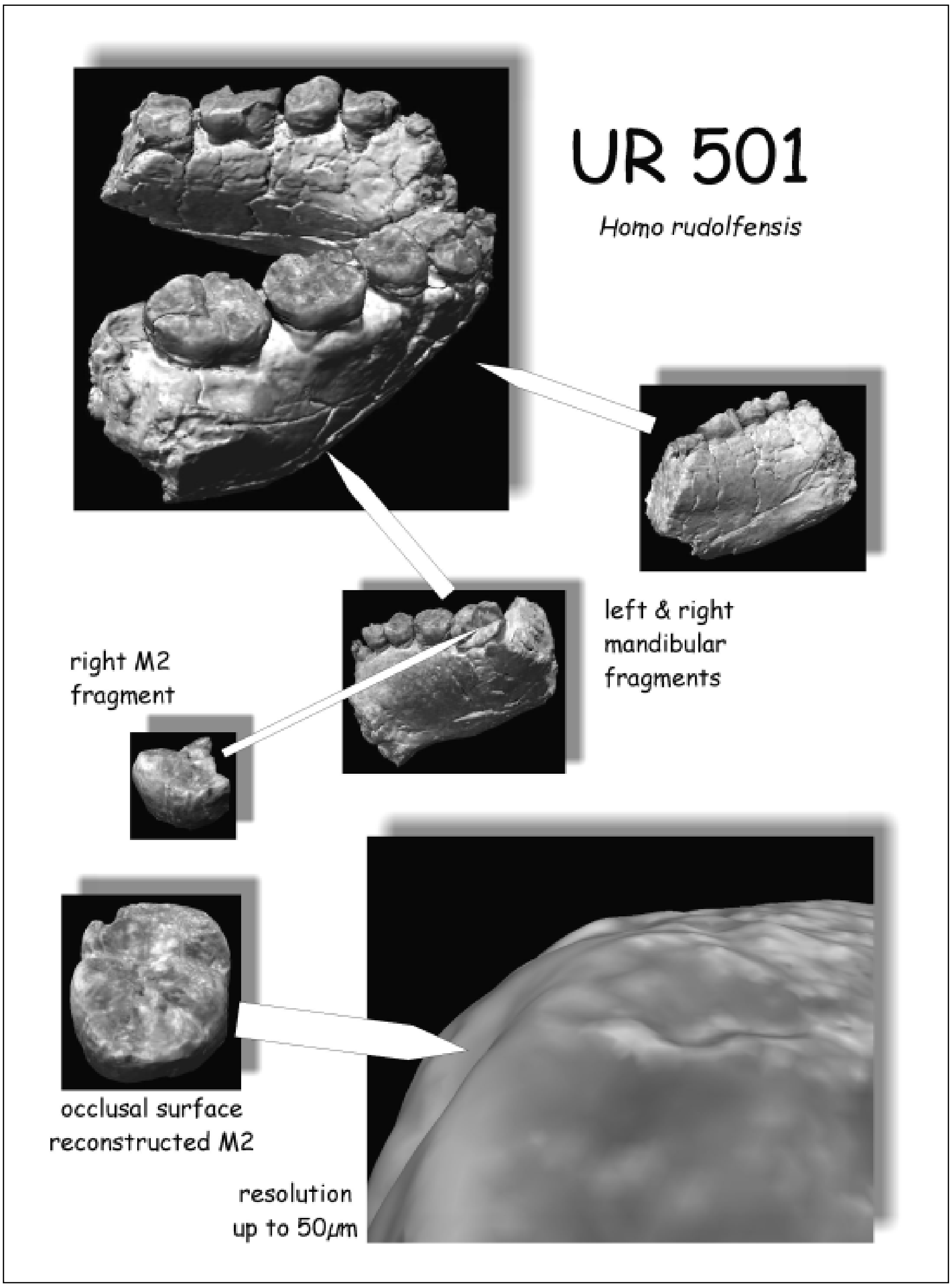


Figure 4 - Rendered virtual 3D surface model and reconstruction of mandible fragments (e.g. early *Homo rudolfensis* jaw UR 501 from the Chiwondo Beds in northern Malawi) derived from optical 3D topometry.

and enamel, and between upper and lower teeth. From the beginning of a tooth's functional life, chewing efficiency increases as its crushing, grinding and shearing surfaces are polished and progressively worn toward some optimum. The optimal point depends on the type of food being chewed. Abrasion rate varies according to the physical properties of nutrition: Soft fruits and meat are less abrasive than tough grass fibres or hard seeds. Abrasion velocity increases if the optimum of attrition resistance is exceeded with wear and food composition stays the same.

Much earlier work on mammalian dental anatomy and function concentrated on size and cusp height measurements (Hylander 1975 a, b, Kay & Hylander 1978), as well as on the functional lengths of enamel ridges (Kay 1978). These comparative studies provided the first clues about the correspondence between macromorphological characteristics and dietary strategies within the same mammalian family. Detailed information is also provided by micro-wear analysis of abrasion patterns on wear facets, pits, and scratches occurring through tooth and food contacts (Teaford, 1985, 1988, 1991, 1994; Teaford & Walker, 1982, 1984; Walker 1979; Walker et al. 1978). Such wear patterns document the relative jaw movements and can be used as a source of information for ecoethology (Janis, 1984; Maier, 1984; Teaford, 1991), although micro-wear reflects only the properties of relatively recent meals of an individual.

Additionally, enamel microstructure and thickness allow conclusions about food properties and diet within rough categories to be reached (Beynon & Dean, 1988; Boyde, 1964; Boyde & Martin, 1982, 1987; Gantt, 1983, 1986; Teaford, 2000; Ungar & Teaford, 2001; Shellis & Hiemae, 1986; Shellis et al., 1998).

Analysis of the spatial position, size, and shape of wear facets offers more detailed information about the dietary niche. These facets are described and numbered by Crompton (1971), Crompton & Hiemae (1970), Kay (1973), Kay & Hiemae (1974), and Maier (1977a, b) and applied to phylogenetic analyses by Maier (1977a, b, 1978a, b) and Maier & Schneck (1981). Maier (1978a, b) and Maier & Schneck (1981) underlined the importance of functional associations of wear facets in comparative studies. Thus studies of the chewing cycles of primitive mammals (Crompton & Hiemae, 1970; Hiemae & Kay, 1973; Kay & Hiemae, 1974), for instance, demonstrating that the chewing process is based on almost similar movements, meant that differences in wear pattern could not be explained by distinct chewing behaviours.

Schmidt-Kittler (1984, 1986) characterized the wear pattern of mammalian teeth through a structural parameter, called the D-value, describing the folding of enamel. Based on this and other enamel parameters he interpreted the occlusal pattern of hypsodont molars in a functional and evolutionary context. Kullmer (1997, 1999) further quantified enamel patterns of the occlusal surface with digital two-dimensional (2D) image processing methods. From the correlation of crown height and occlusal surface length with the degree of folding (D-value) in different wear stages, it is possible to model the crown architecture and function (Kullmer, 1999).

This method is limited to relatively flat surfaces, since only a low topographic relief can be reasonably analysed from two dimensional image data sets. Measurement errors occur if we use two-dimensional methods to calculate enamel occlusal surface areas on high topographic relief (Maier, 1980; Janis, 1990). Three-dimensional documentation of tooth surfaces have been accomplished by several research groups. Specific methods of microscopy, such as confocal laser microscopy employed for very small teeth (< 10mm) (Jernvall & Selänne, 1999) and reflex microscopy (Reed, 1997; Strait, 1993), have yielded the first results.

Using Geographic Information System technology developed for the presentation and analysis of landscape surfaces it is feasible to model the crown relief as three-dimensional "landscape", permitting the measurement of cusp volumes and occlusal basins (Zucotti et al., 1998). Zucotti et al. (1998) used an electromagnetic 3D digitising system (Polhemus 3Space) to acquire tooth crown landmark data. However, while this technique is reasonable for relatively large tooth crowns, providing a maximum resolution of about 0.13 mm, the data recording procedure employs a handheld stylus which is consequently relatively time consuming.

Ungar & Williamson (2000) used a laser scanner (RPS 4500 Laserdesign) with a resolution of 0.0254 mm for measuring tooth surfaces. The fixed two-dimensional scan architecture of laser systems consists of a complex opto-mechanical system (Breuckmann, 1993) whose mechanical scanning platform is very limited in object size. Often it is necessary to produce casts of teeth, instead of scanning the original directly because of its attachment to facial skeletal remains.

3D MORPHOMETRICS OF TOOTH CROWNS

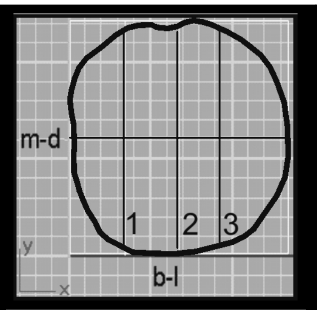
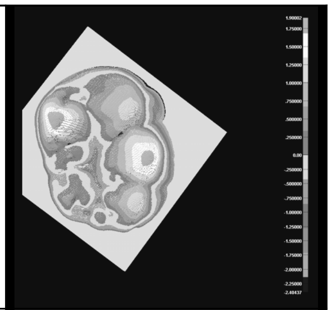
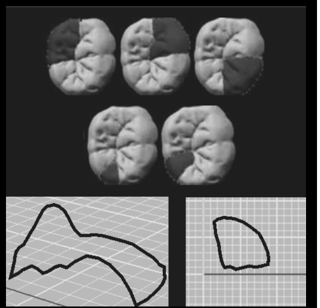
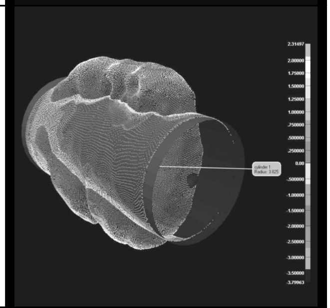
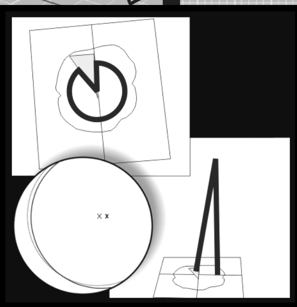
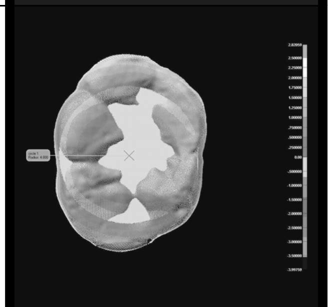
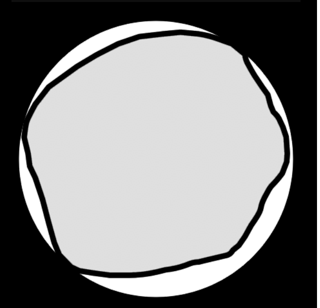
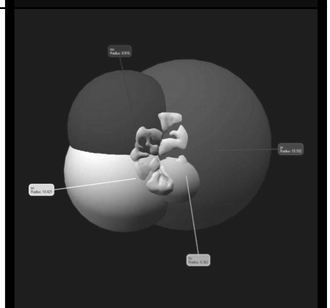
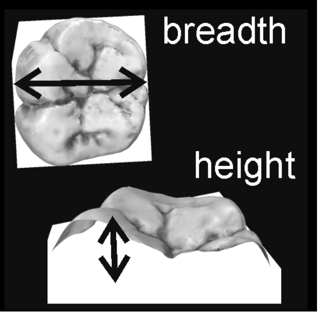
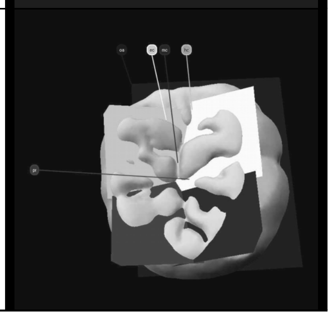
The use of 3D datasets for pattern analysis and comparison depends on two major factors. First, the investigator must decide if the method and technique of data acquisition is appropriate in resolution and accuracy to permit the analysis of the region(s) of interest on a specimen. Second, it is important to know the parameter settings of the scanning system in order to estimate the quality of the data. Given suitable imaging conditions, VR reconstructions can be used to extract a wide range of measurements in a virtual environment without touching the original. For instance, the exact location where measurements are taken can be recorded by point-to-point marking in 3D space. Structural parameters, like those for hominid teeth, defined and listed by Wood (1991), can be measured within seconds. As examples, for all specimens examined in this study we provide HOTPAD measurements in Table 1.

Besides distance parameters, Wood (1991) also documented cusp and occlusal surface areas in 2D. To obtain these areas, tracings of photographs were digitised according to the anatomical expertise of the operator, and thus it is very difficult to know the exact margins used for any particular specimen. In virtual reality we can indicate the boundaries on the 3D model and computationally calculate 3D areas. Precise 2D areas are measured after projecting, say, cusp areas of a tooth to a reference plane. Reference planes are necessary if one is to compare data from different teeth controlled for position and orientation. Choosing a proper reference is difficult to define and one should always choose a reference with knowledge of variability and variation.

How shall we choose the best reference plane? The application of landmark methods is limited to precisely defined morphological features. Therefore landmarks cannot help very much in tooth crown examination, since surface morphology changes with wear. We believe that the cervical plane can be used as a reference for the purpose of relief quantification (Figure 5). Wood and Abbott (1983), Wood et al. (1983) and Wood and Uytterschaut (1987) described the calculation of molar base crown, cusp, and premolar base crown and cusp areas, respectively, relative to the cervical plane in 2D, as noted above. In this method, area measures relative to the cervical plane were taken from teeth by means of photographic imaging of the occlusal surface whilst the cervical margin lay perpendicular to the optical axis.

Table 1 - List of structural parameters of tooth crowns provided in HOTPAD, e.g. for molars.

Structural Parameters of Molars (M)

linear measurements **2D [mm]** (after Wood (1991): № 313-316; including qualitative parameters № 327, 331-340)		**surface elevation** **model** [mm, % (deviation), x, y, z] (surface relief to occlusal plane)	
cusp areas 3D + 2D [mm²] (2D: after Wood (1991): № 319-327, 328+329) ***3D index*** (3D area/2D area)		**best fit** **cylinder radius &** **orientation** [mm, % (deviation), x, y, z] (surface models)	
strike and dip cusp sloping, wear facets [°] (stereoplot)		**best fit** **circle radius &** **orientation** [mm, % (deviation), x, y, z] (surface models)	
circularity index (2D surface area / max. bounding circle area)		**best fit** **sphere radius &** **orientation** [mm,% (deviation), x, y, z] (fitting in surface model, cusp areas, wear facets)	
height index (max. breadth/ max. height) (surface model, cusps)		**best fit** **plane orientation** [x, y, z] (fitting in cusp areas, wear facets)	

In our study the cervical plane is computationally determined by means of the least squares best fit method. Interactively the cervical margin is marked on the VR model by drawing a closed curve. Afterwards the plane is fitted through all points in 0.5mm distance to curve. The plane is then moved apically toward the deepest point of the fissure pattern. The reference plane cuts the VR model in this position. Further calculations on the occlusal surface are limited to the crown area above the plane which includes the complete occlusal surface. Orientation in the mesio-distal direction remains complicated however. To make orientation measures, such as the strike and dip of cusp slopes, we use the tangents method (Figure 5). In occlusal view we compute two tangents along the lingual and buccal margins. The midpoint between these sub-parallel

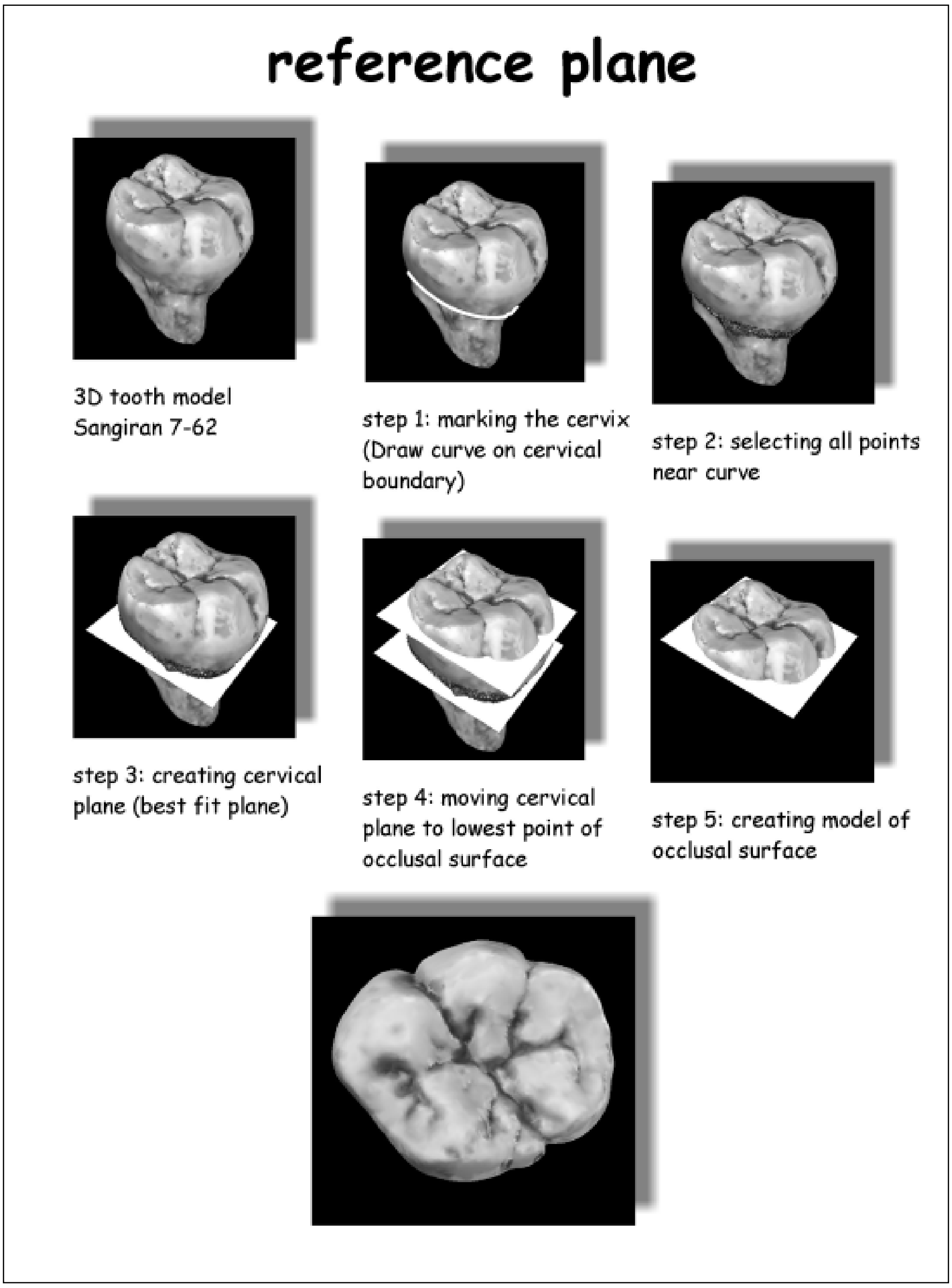


Figure 5 - Creating the cervical plane on a virtual model as reference for analyses of occlusal surfaces using the PolyWorks software package.
Step 1: Draw curve on cervix interactively. Step 2: Selecting all points near curve (distance 0.5mm). Step 3: Creating best fit plane through points. Step 4: Align coordinate system (x,y) to cervical plane and move plane towards lowest point of the fissure pattern. Step 5: Cut model with plane and reconstruct occlusal surface model for morphometric analysis.

tangents is located and a precise mesio-distal longitudinal axis chord is formed, similar to the 3D method outlined by Bromage et al. (1995).

Slope is calculated by fitting a plane into the marked cusp slope. Strike and dip of the fitted plane is extracted by common geological methods. The results can be visualized in a stereoplot diagram (Figure 6). Each great circle and pole reflects the overall orientation of slope of a defined area on the tooth surface. The steeper the relief the closer is the pattern of great circles located around the centre of the diagram. Each occlusal surface will be represented by its individual stereoplot pattern. Additionally we can use stereoplot diagrams to quantify the wear facets (Figure 7) on the occlusal surface to determine wear stages and to analyse and document shearing and grinding capacities of teeth (Kullmer et al., in prep).

DISCUSSION AND PERSPECTIVES OF 3D TOPOMETRY

Summarizing the main features of optical 3D topometry, we may point out its potential as follows:

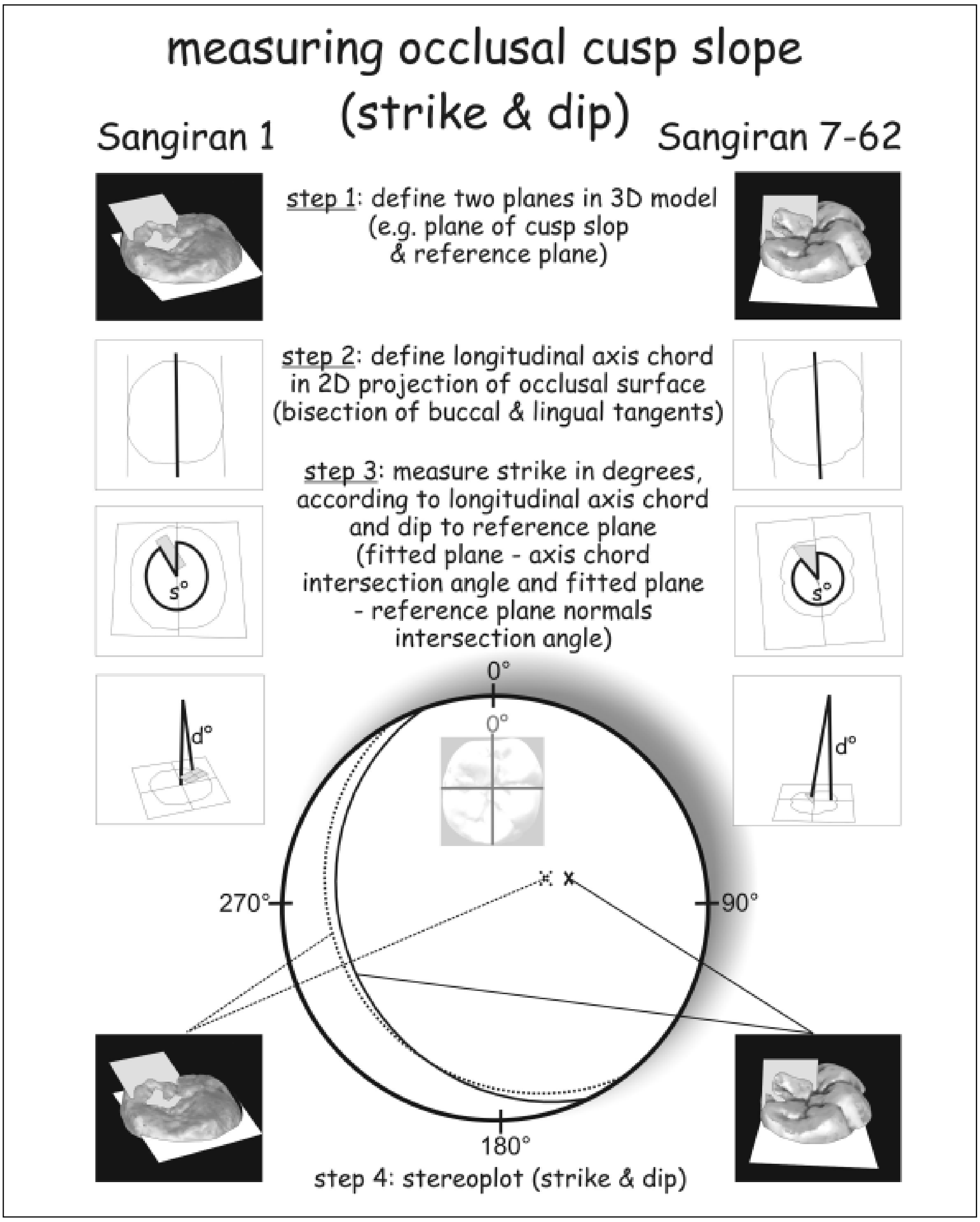


Figure 6 - Measuring cusp sloping, including strike and dip in degrees.
Step 1: Defining cervical plane as reference and plane of cusp sloping, using the best fit least square method. Step 2: Defining mesio-distal longitudinal axis chord in 2D projection of occlusal surface boundary, using buccal and lingual tangents. Step 3: Measuring strike in degrees according to longitudinal axis chord and dip to reference plane orientation. Step 4: Presentation of strike and dip in a stereoplot diagram. Position of great circles and poles in the lower hemisphere projection reflecting average orientation of occlusal cusp slope.

- Fast 3D digitising of object surfaces of modern and fossil originals.
- High accuracy
- High resolution
- Large dataset
- Non-contact data acquisition
- High flexibility in object size
- Portable system

However, not all objects are suitable for this method, depending on the particular question. The choice of the measuring volume is an important factor, since the maximum resolution for the VR model is restricted. It is important to know in advance on which details the investigation takes place before scanning the object. The measuring of very complex objects can lead to problems during scanning, resulting in missing data because of shadows and deep cavities on the surface. Very dark or even black specimens cannot be measured without powdering to uniformly lighten the surface. Rapidly and intensely changing lights should be avoided, since otherwise no exact calculation of light intensities is possible and the measuring sequence has to be repeated. However,

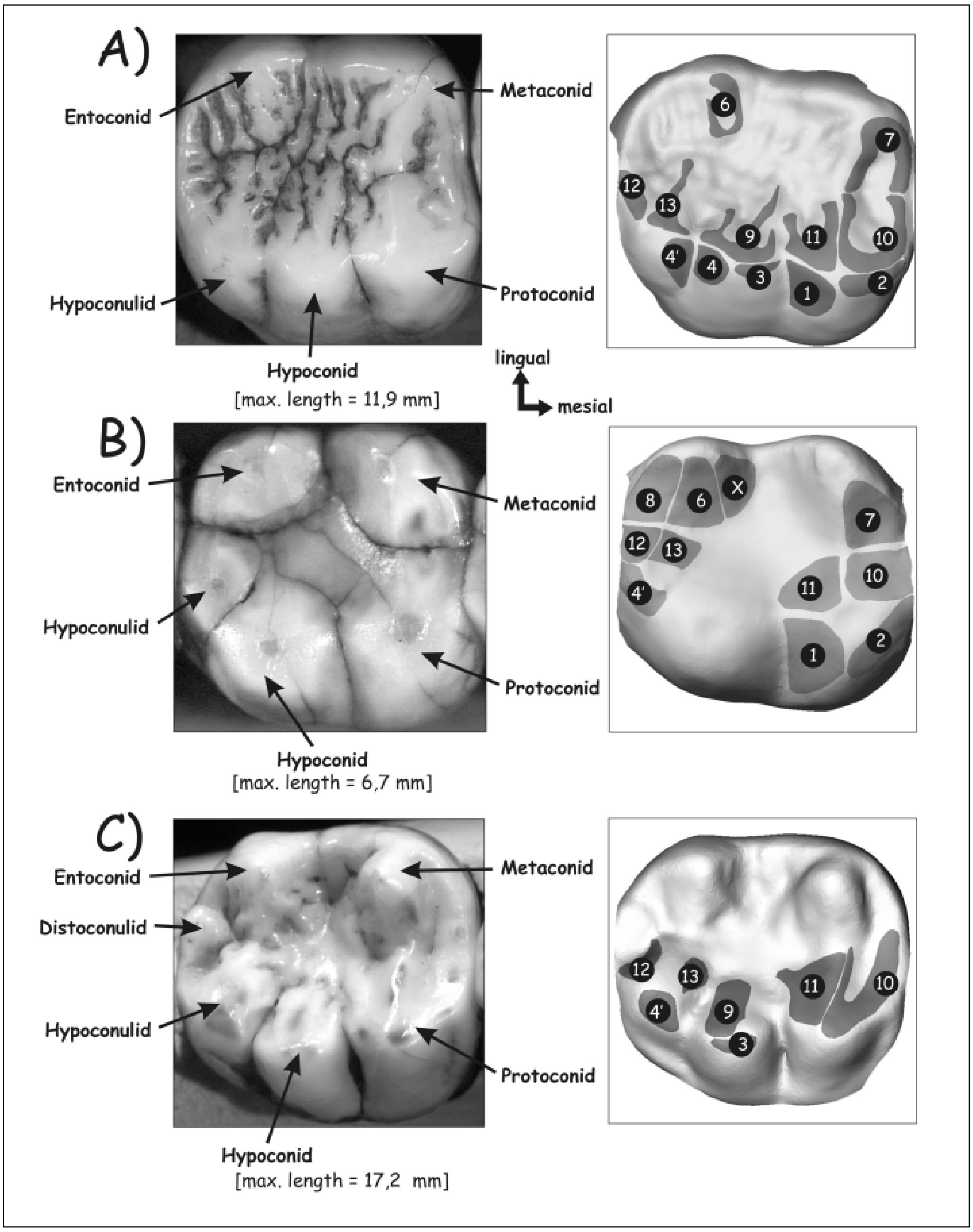


Figure 7 - A) (left) Digital image of lower right M2 of an orang-utan (*Pongo pygmaeus*), (right) virtual 3D model with marked wear facets (numbering after Crompton, 1971, Kay 1973 and Maier 1977). Facets 8 and 5 are not identifiable, because of crenulated enamel.
B) (left) Digital image of lower right M2 of a gibbon (*Hylobates hoolock*), (right) virtual 3D model with marked wear facets (numbering after Crompton, 1971, Kay 1973 and Maier 1977). Facets 3,4 and 9 are missing, because of rounded, dome-shaped hypoconid. An additional facet (x) is observed, close to entoconid. Facet 5 is missing. C) (left) Digital image of lower right M2 of a gorilla (*Gorilla gorilla*), (right) virtual 3D model with marked wear facets (numbering after Crompton, 1971, Kay, 1973 and Maier, 1977). Facets 1, 2, 4, 5, 6, 7 and 8 are not identifiable on the gorilla M2.

some of the limitations of the system can be influenced positively by individual system parameter settings, depending on object properties as noted above and the scan environment.

The optical 3D topometry possesses some important advantages for the use in palaeontology and archaeology compared to alternative measuring techniques, such as high flexibility in object size and portability. High resolution 3D surface data extends morphometric possibilities enormously. The fast measuring of surface structure in space replaces time-consuming measuring procedures and provides more accurate and precise data. Presently 3D scanning techniques are tested in many fields of palaeontology. Digital 3D data are used for structural analysis, virtual reconstruction, animation, presentation and archives. Remarkable are the didactic possibilities of computer animation and reconstruction. One can magnify the digital model by the computer to reproduce an enlarged replica via stereo-lithography or modern 3D printing devices. HOTPAD is the first attempt to document a hominid collection with high-resolution VR models of specimens to demonstrate the potential of 3D digital image processing. The current project should be understood to be an exploration into the universe of Virtual Reality in palaeoanthropology. In the near future digital techniques like optical topometry will join with computer tomography and confocal microscopy to illuminate new 3D aspects in palaeontological research.

SUMMARY

HOTPAD (Hominid tooth pattern database) is a high quality digital archive of virtual models. It can be used as a catalogue to provide colleagues and interested parties all over the world the chance to estimate the value of specimens in an archived collection for their research.

The use of digital three-dimensional (3D) image processing systems permits the extraction of structural parameters within seconds and, together with modern scanning techniques, opens an entirely new perspective for morphological analysis in palaeobiology.

In this contribution we document a novel 3D technique for the evaluation and quantification of hominid specimens collected by G.H.R von Koenigswald in Indonesia. The resultant database will be used for more extensive studies on this important assemblage.

The optical topometry system used by us (Breuckmann) consists of a sensor with a power supply and a notebook computer (PIII 650Mhz, 20Gb HD). The sensor is connected to a tripod and can be rotated in all directions. The whole system is portable and fits into one small box. It can be transported to museums for digitising collections with a resolution up to 50µm.

After digitising, the calculated Virtual Reality (VR) model can be analysed in absence of the original. The VR models are placed in a tooth pattern database called HOTPAD which can be viewed from a normal Internet browser. One can use HOTPAD as an information centre on hominid tooth patterns or just to look at specimens to assess their completeness. But further, information about the 3D scanning, measurement lists, and comparisons of results of the fossil material are also available. The first version of HOTPAD contains molar material from Sangiran. As an add-on we include the fossil skull fragments of this collection. VR models in different resolutions are available for downloading, including measurements for the purpose of study and analysis. HOTPAD contains conventional measurements, like distance parameters based on the definitions of Wood (1991) and complex 3D measurements, including relative parameters such as circularity and relief indices. 2D and 3D areas of cusps and occlusal surface are also provided. Furthermore, industrial 3D software, normally used for the inspection of product parts, allows us to view the exact elevation of each calculated 3D point. HOTPAD should be understood as a contribution to enlighten the possibilities of using modern 3D techniques to judge queries in palaeontological and palaeoanthropological research.

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BIBLIOGRAPHY

BEYNON, A.D. & Dean, M.C., 1988, Distinct dental development patterns in early fossil hominids. - *Nature* 335, 509-514.

BEYNON, A.D. & WOOD, B.A., 1986, Variations in Enamel Thickness and Structure in East African Hominids. - *Am. J. Phys. Anthrop*. 70, 177-193.

BOYDE, A., 1964, *The structure and development of mammalian enamel*. - Ph.D. Thesis. Univ. of London.

BOYDE, A. & MARTIN, L.B., 1982, Enamel microstructure determination in hominoid and cercopithecid primates. - *Anat. Embryol*. 165, 193-212.

BOYDE, A. & MARTIN, L.B., 1987, Tandem Scanning Reflected Light Microscopy of Primate Enamel. - *Scanning Microscopy 1*, 1935-1948.

BREUCKMANN, B., 1993, *Bildverarbeitung und optische Meßtechnik in der industriellen Praxis*. - Franzis, München, 1993, S. 1-315.

BROMAGE, T.G., SCHRENK, F. & ZONNEVELD, F.W., 1995, Palaeoanthropology of the Malawi Rift: An early hominid mandible from the Chiwondo Beds, northern Malawi. *Journal of Human Evolution* 28, 71-108.

CROMPTON, A.W., 1971, The origin of the tribosphenic molar. - *Zool. J. Linn. Soc*. 50 (Suppl.), 65-87.

CROMPTON, A.W. & HIIEMAE, K.A., 1970, Molar occlusion and mandibular movements during occlusion in the American opossum, Didelphis marsupialis L. - *Zool. J. Linn. Soc*. 49, 21-47.

GANTT, D.G., 1983, *The Enamel of Neogene Hominoids. Structural and Phyletic Implications*. - In *New Interpretations of Ape and Human Ancestry*, edited by R.L. Ciochon, & R.S. Corruccini, 1983, New York/London: Plenum Press, 249-298.

GANTT, D.G., 1986, Enamel Thickness and Ultrastructure in Hominoids: With Reference to Form, Function and Phylogeny. - In *Comparative Primate Biology*, edited by D.R. Swindler & J. Erwin, Vol. 1: Systematics, evolution and anatomy. 1986, New York: Alan R. Liss, 453-475.

GRINE, F. E. & FRANZEN, J. L., 1994, Fossil Hominid Teeth from the Sangiran Dome (Java, Indonesia). *Cour. Forschungsinstitut Senckenberg*, 171: 75-103, 1 Tab., 4 Pls.

HIIEMAE, K.M. & KAY, R.F., 1973, Evolutionary Trends in the Dynamics of Primate Mastication. - In *Symp IVth Int. Congr. Primat., vol. 3: Craniofacial Biology of Primates*. 1973, Basel: Karger, p.28-64.

HYLANDER, W.L., 1975a, Incisor Size and Diet in Anthropoids with Special Reference to Cercopithecidae. - *Science* 189, 1095-1098.

HYLANDER, W.L., 1975b, Incisor Size and Diet in Cercopithecidae. - *Am. J. Phys. Anthrop*. 42, 309.

JANIS, C.M. , 1984, Predictions of primate diets from molar wear pattern. In *Food Acquisition and Processing in Primates* edited by Chivers, B.A. et al. 1984, Plenum Publishing Corporation, p.331-340.

JANIS, C.M., 1990, The correlation between diet and dental wear in herbivorous mammals, and its relationship to the determination of diets of extinct species. In *Evolutionary Paleobiology of Behaviour and Coevolution* edited by A.J. Boucot. 1990, Amsterdam: Elsevier Science Publishers B.V., p.241-259.

JERNVALL, L. & SELÄNNE, L. (1999). Laser confocal microscopy and geographic information systems in the study of dental morphology.- *Palaeontologica Electronica*, Vol. 2(1): http://www-odp.tamu.edu/paleo/1999_1/confocal/issue1_99.htm.

KAY, R.F., 1978, Molar Structure and Diet in Extant Cercopithecidae. - In *Development, Function and Evolution of Teeth*, edited by P. Butler & K. Joysey. 1978, New York/London: Academic Press, p.309-339.

KAY, R.F. & HIIEMAE, K.M., 1974, Jaw movement and tooth use in recent and fossil primates. - *Am. J. Phys. Anthrop*. 40, 227-256.

KAY, R.F. & HYLANDER, W.L., 1978, The Dental Structure of Mammalian Folivores with Special Reference to Primates and Phalangeroidea (Marsupialia). - In *The Ecology of Arboreal Folivores* edited by G.G. Montgomery. 1978, Washington: Smithonian Institute Press, p.173-191.

KOENIGSWALD, G.H.R. von, 1940, Neue Pithecanthropus-Funde 1936-1938. Ein Beitrag zur Kenntnis der Praehominiden.- *Wet. Meded.,* 28: 1-232.

KOENIGSWALD, G.H.R. von, 1950, Fossil hominids of the lower Pleistocene of Java.- *Proc. Int. Geol. Congr. Gr. Britain* 1948, Part 9, sect. H: 59-61.

KOENIGSWALD, G.H.R. von, 1954, The Australopithecinae and Pithecanthropus. I – III. – *Proc. kon. nederl. Akad. Wet*. (B) 56: 403-413; (B) 56: 427-438; (B) 57: 85-91.

KULLMER, O. (1997). *Die Evolution der Suiden im Plio-Pleistozän Afrikas und ihre biostratigraphische, paläobiogeographische und paläoökologische Bedeutung*. - Dissertation im Fachbereich Geowissenschaften der Johannes Gutenberg-Universität, Mainz, pp.143.

KULLMER, O., 1999, Evolution of African Plio-Pleistocene Suids (Artiodactyla: Suidae) Based on Tooth Pattern Analysis. - *Kaupia, Darmstädter Beiträge zur Naturgeschichte* 9, 1-34.

KULLMER, O., SCHRENK, F., DÖRRHÖFER, B., in press, High resolution 3d-image analysis of ape, hominid and human footprints. *Cour. Forschungsinstitut Senckenberg*.

KULLMER, O., ENGEL, K. & SCHRENK, F., in prep, Moderne dreidimensionale Vermessungstechniken erweitern paläontologische Forschung - Virtuelle Zahnmodelle ermöglichen die Analyse komplexer Zahnoberflächen.

MAIER, W., 1977a, Die Evolution der bilophodonten Molaren der Cercopithecoidea. Eine funktionsmorphologische Untersuchung. - *Z. Morph. Anthrop*. 68, 26-56.

MAIER, W., 1977b, Die bilophodonten Molaren der Indriidae (Primates) - ein evolutionsmorphologischer Modellfall. - *Z. Morph. Anthrop*. 68, 307-344.

MAIER, W., 1978a, Zur Evolution des Säugetiergebisses - Typologische und konstruktionsmorphologische Erklärungen. - *Natur und Museum* 108(10), 288-300.

MAIER, W., 1978b, Die Evolution der tribosphenischen Säugetiermolaren. - *Sonderbd. Naturwiss. Verh*. 3, 41-60.

MAIER, W., 1980, Konstruktionsmorphologische Untersuchungen am Gebiß der rezenten Prosimiae (Primates). - *Abhandlungen der Senckenbergischen Naturforschenden Gesellschaft* 538, 1-158.

MAIER, W., 1984, Tooth Morphology and Dietary Specialization. - In *Food Acquisition and Processing in Primates* edited by D.J. Chivers. 1984, Plenum Publishing Corporation, p.303-330.

MAIER, W. & SCHNECK, G., 1981, Konstruktionsmorphologische Untersuchungen am Gebiß der hominoiden Primaten. - *Z. Morph. Anthrop*. 72, 127-169.

REED, D.N.O., 1997, Contour mapping as a new method for interpreting diet from tooth morphology. - *Am. J. Phys. Anthrop*., Suppl. 24, 194.

SCHMIDT-KITTLER, N., 1984, Pattern analysis of occlusal surfaces in hypsodont herbivores and its bearing on morphofunctional studies. - *Koninkl. Nederl. Acad. Wetensch., Proceeding*s B 87 (4), 453-480.

SCHMIDT-KITTLER, N., 1986, Evaluation of occlusal patterns of hypsodont rodent dentitions by shape parameters. - *N. Jb. Geol. Paläont*. Abh. 173(1), 75-98.

SHELLIS, R.P. & HIIEMAE, K.M., 1986, Distribution of Enamel on the Incisors of Old World Monkeys. - *Am. J. Phys. Anthrop*. 71, 103-113.

SHELLIS, R.P., BEYNON, A.D., REID, D.J. & HIIEMAE, K.M., 1998, Variation in molar enamel thickness among primates. - *J. Hum. Evol*. 35(4/5), 507-522.

STRAIT, S.G., 1993, Differences in occlusal morphology and molar size in frugivores and faunivores. *J. Hum. Evol*. 25(6), 471-482.

TEAFORD, M.F., 1985, Molar microwear and diet in the genus Cebus. - *Am. J. Phys. Anthrop*. 66, 363-370.

TEAFORD, M.F., 1988, A review of dental microwear and diet in modern mammals. - *Scanning Microscopy 2*, 1149-1166.

TEAFORD, M.F., 1991, Dental microwear: What can it tell us about diet and dental function? - In *Advances in Dental Anthropology* edited by M. A. Kelley & C. S. Larsen. 1991, New York: Wiley-Liss, p.341-356.

TEAFORD, M.F., 1994, Dental microwear and dental function. - *Evol. Anthrop*. 3, 17-30.

TEAFORD, M.F., 2000, Primate dental functional morphology revisited. – In *Development, Function and Evolution of Teeth* edited by M. F. Teaford, M. M. Smith & M. W. J. Ferguson. pp. 314, Cambridge University Press.

TEAFORD, M.F. & WALKER, A., 1982, Dental microwear: mechanisms and interpretations. - *Am. J. Phys. Anthrop*. 62, 236.

TEAFORD, M.F. & WALKER, A., 1984, Quantitative differences in dental microwear between primate species with different diets and a comment on the presumed diet of Sivapithecus. - *Am. J. Phys. Anthrop*. 64, 191-200.

UNGAR, P.S. & WILLIAMSON, M., 2000, Exploring the effects of tooth wear on functional morphology: A preliminary study using dental topographic analysis. - *Palaeontologica Electronica*, Vol. 3(1): http://www-odp.tamu.edu/paleo/2000_1/gorilla/issue1_00.htm.

UNGAR, P.S. & TEAFORD, M., 2001, The Dietary Split Between Apes and the Earliest Human Ancesters.- In *Humanity from African Naissance to Coming Millenia,* edited by P. V. Tobias, M. A. Raath, J. Moggi-Cecchi, G. A. Doyle. pp. 409, Firenze University Press.

WALKER, A., 1979, S.E.M. Analysis of Microwear and its correlation with dietary patterns. - *Am. J. Phys. Anthrop*. 50, 489.

WALKER, A., HOECK, H.N. & PEREZ, L., 1978, Microwear of mammalian teeth as an indicator of diet. *Science* 201, 908-910.

WOOD, B., 1991, *Hominid Cranial Remains. Koobi Fora Research Project. 4*. Oxford: Clarendon.

WOOD, B.A., 1993, Early Homo: How many species? In *Species, Species Concepts, and primate Evolution*, edited by W.H Kimbel. & L.B. Martin. pp. 485-522, New York: Plenum Press.

WOOD, B.A. & ABBOTT, S.A., 1983, Analysis of the dental morphology of Plio-Pleistocene hominids: I. Mandibular molars: crown area measurements and morphological traits. *J. Anat*. 136, 197-219.

WOOD, B.A. & UYTTERSCHAUT, H., 1987 Analysis of the dental morphology of Plio-Pleistocene hominids: III.Mandibular premolar crowns. *J. Anat.* 154, 121-156.

ZUCCOTTI, L.F., WILLIAMSON, M.D., LIMP, W.F., UNGAR, P.S., 1998, Modeling primate occlusal topography using geographic information systems technology. - *Am. J. Phys. Anthrop*. 107, 137-142.